The Role of Subsoil Properties for Phosphorus Leaching in Agricultural Soils

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Cover: Mellby sand soil profile, lysimeter collection and lysimeter station.
(photo: Helena Andersson)

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Abstract

Phosphorus (P) leaching from agricultural land is a large contributor to eutrophication of many surface waters and the Baltic Sea. Better knowledge of P sorption and release in the subsoil could enable the development of effective mitigation strategies for P leaching. This thesis examined the impact of soil properties on P leaching from four Swedish agricultural soils (two clays, two sands), using intact soil columns extracted with (length 1.05 m) and without (length 0.77 m) topsoil. The role of the subsoil as a source or sink for P leaching was also investigated, and placement of quicklime (CaO) on top of the subsoil as a mitigation strategy for P leaching was evaluated.

Leaching of dissolved reactive P (DRP) from subsoil lysimeters was 94% of that from full-length lysimeters in one of the clay soils, and 70% in the other. The higher contribution of the former clay subsoil was probably due to high P content deeper in the soil. Leaching of DRP was low from full-length and subsoil lysimeters (0.12 and 0.08 kg ha^{-1} yr^{-1}, respectively) in one of the sandy soils, despite high topsoil P content, due to high P sorption capacity and low degree of P saturation in the subsoil. However, leaching of DRP was very high from full-length and subsoil lysimeters (3.33 and 3.29 kg ha^{-1} yr^{-1}, respectively) from the other sandy soil with moderate topsoil P content, due to high P content and low P sorption capacity in the subsoil. These results indicate that the subsoil can function as both a source and sink for P leaching.

Phosphorus leaching increased with increasing P content and DPS in subsoil and decreasing P sorption capacity in topsoil and subsoil, indicating that these parameters could be used for P leaching risk assessments. However, on soils with preferential flow in the subsoil, P leaching may be high despite high subsoil P sorption capacity. Hence, both chemical and physical properties of topsoil and subsoil must be considered in implementation of appropriate, cost-effective mitigation strategies for P loss reductions.

Application of lime on top of the subsoil significantly reduced leaching of particulate P (PP) in both clay subsoils by 49 and 51%, respectively, compared with unlimed controls. This suggests that subsoil liming might be an appropriate method to reduce P leaching from clay soils.

Keywords: phosphorus leaching, subsurface drainage, subsoil, lysimeter, mitigation options, phosphorus sorption, lime

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Dedication

Till mina tre ♥ ♥ ♥

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Andersson, H., L. Bergström, F. Djodjic, B. Ulén and H. Kirchmann (2013). Topsoil and subsoil properties influence phosphorus leaching from four agricultural soils. *Journal of Environmental Quality* 42 (2), 455-463.

II Andersson, H., L. Bergström, B. Ulén, F. Djodjic and H. Kirchmann (2015). The role of subsoil as a source or sink for phosphorus leaching. *Journal of Environmental Quality* 44 (2), 535-544.

III Andersson, H., L. Bergström, F. Djodjic, B. Ulén and H. Kirchmann (2016). Lime placement on subsoil as a strategy to reduce phosphorus leaching from agricultural soils. *Submitted manuscript*.

The contribution of Helena Andersson to the papers included in this thesis was as follows:

I Planned the study together with the co-authors. Performed the experimental work, data analyses, data interpretation and writing with assistance from the second author.

II Planned the study together with the co-authors. Performed the experimental work, data analyses, data interpretation and writing with assistance from the second author.

III Planned the study together with the co-authors. Performed the experimental work, data analyses, data interpretation and writing with assistance from the second author.

Abbreviations

AL	Soil extraction method with ammonium lactate
DPS	Degree of phosphorus saturation
DRP	Dissolved reactive phosphorus
PP	Particulate phosphorus
PSI	Phosphorus sorption index
TP	Total phosphorus

1 Background

Eutrophication is a major environmental problem in many parts of the world, and in several inland surface waters in Sweden and the Baltic Sea. Agriculture contributes approximately 40% of Sweden's anthropogenic net phosphorus (P) load to the Baltic Sea (Brandt *et al.*, 2009), which makes it the largest diffuse source of P input to the sea (HELCOM, 2011). In 2000, the EU Water Framework Directive, which requires good ecological quality in *e.g.* inland surface waters and coastal waters, was implemented. In addition, in 2007, the Baltic Sea Action Plan (BSAP), which aims at achieving good ecological status in the Baltic Sea, was adopted (HELCOM, 2013). Reducing P losses from agricultural land is therefore a major concern.

For a long time, erosion and surface runoff were considered to be the main pathway for P losses from agricultural land (Sharpley *et al.*, 1993). However, in recent years, awareness has increased regarding P losses through subsurface flow and tile drains (*e.g.* King *et al.*, 2015b; Mellander *et al.*, 2012; Djodjic *et al.*, 1999; Sims *et al.*, 1998).

Due to the previous focus on surface runoff, most research has emphasised topsoil characteristics for P loss estimations, and several have found significant correlations between increased P content in topsoil and P losses (*e.g.* Maguire & Sims, 2002; Heckrath *et al.*, 1995). On the other hand, topsoil properties have often proven to be insufficient for estimating P leaching through the entire soil profile (Djodjic *et al.*, 2004; Jensen *et al.*, 1999). Consequently, the importance of subsoil properties for P leaching has frequently been pointed out (*e.g.* Liu *et al.*, 2012c; Sinaj *et al.*, 2002; Schoumans & Groenendijk, 2000). However, knowledge about movement, sorption and desorption of P in the subsoil is limited. In the subsoil, P can be bound to aluminium (Al) and iron (Fe), and at high pH also to calcium (Ca). This may result in lower P leaching from the entire soil profile than could be expected from studying the P content or P leaching from the topsoil only. In most soil profiles, P content is higher in

the topsoil than in the subsoil (Rubaek *et al.*, 2013). However, due to natural enrichment or frequent P fertilisation, subsoil P content may be high (Kronvang *et al.*, 2009; Sims *et al.*, 1998). This may result in higher P leaching from the entire soil profile than expected from just studying the topsoil P content and P leaching from the topsoil. Hence, the subsoil may act either as a source or sink for P leaching, and may even have a greater impact on P leaching than different agricultural practices or mitigation options carried out in the topsoil. It is therefore necessary to be aware of both topsoil and subsoil properties in the field in order to apply proper strategies for P leaching reduction.

In soils where the subsoil does not act as a sink for P, actions need to be taken to reduce P leaching. However, access to good, well-tested and cost-effective mitigation options for P leaching from agricultural land is limited, mainly due to the lack of knowledge about the behaviour of P in soil, and especially in subsoil.

One mitigation option used today to reduce P losses is addition of reactive materials to immobilise P in soil or to trap P as it moves through the landscape (Bryant *et al.*, 2012; Chardon *et al.*, 2012; Egemose *et al.*, 2012; Kirkkala *et al.*, 2012). In Sweden, adding quicklime (CaO) or hydrated lime ($Ca(OH)_2$) to clay topsoils is officially recommended by the Swedish Board of Agriculture to improve soil structure and thereby reduce P losses (SBA, 2014). However, adding lime to topsoil may decrease the plant availability of P (Murphy & Stevens, 2010; Curtin & Syers, 2001), and lime placed between topsoil and subsoil (at about 25-30 cm depth) could thus be an option to reduce P leaching while still maintaining high P availability for plants in the topsoil.

This PhD-thesis analyses the impact of different topsoil and subsoil properties on P leaching and investigates whether some Swedish agricultural subsoils act as a source or sink for P leaching. It also examines the potential of lime placed on subsoil as a mitigation option for P leaching. Figure 1 illustrates how the three papers included in the thesis are interrelated and shows the main research focus and study method described in each paper.

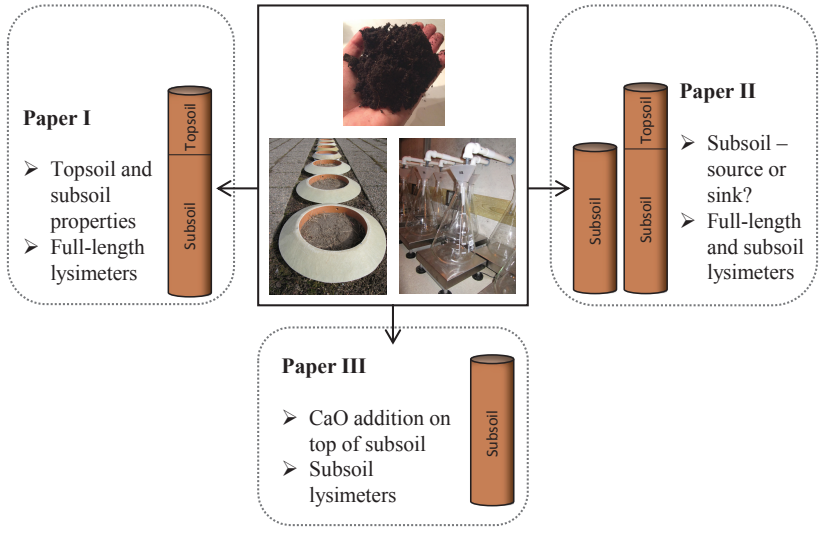

Figure 1. Overview of the relationship between Papers I-III in this thesis. All three papers involved soil analyses and lysimeter studies. Photo: Helena Andersson.

1.1 Phosphorus in soil

Phosphorus is present in the soil in both inorganic and organic form. Weathering of apatite, the most common phosphate mineral in the earth's crust, is the main source of inorganic P in natural, undisturbed soils. In acidic soils, secondary P minerals formed are mainly aluminium (Al) and iron (Fe) phosphates, whereas different types of secondary calcium (Ca) phosphates dominate in neutral to alkaline soils (Smeck, 1985). Phosphorus can also be sorbed to clay particles, $CaCO_3$ (calcareous soils) and by Al and Fe oxides and hydroxides (acid soils). When inorganic P is taken up by plants and microorganisms, it is transformed to different forms of organic P, followed by continuous turnover of P through mineralisation and immobilisation (Figure 2). Between 30 and 65% of total P in soils is commonly in organic form (Harrison, 1987).

Since P is present in the soil as primary or secondary minerals, as stable soil organic P and as P bound to Al and Fe sites (Lookman *et al.*, 1995), it is only available for plant uptake through dissolution, mineralisation or desorption (Figure 2). Dissolved P in the soil solution constitutes a very small proportion of total P in soil, and is present mainly as HPO_4^{2-} in alkaline soils and as $H_2PO_4^-$ in acid soils (Pierzynski *et al.*, 2005). Due to crop uptake, the soil solution therefore needs to be replenished with P during the growing season, in order to maintain high crop production (Frossard *et al.*, 2000).

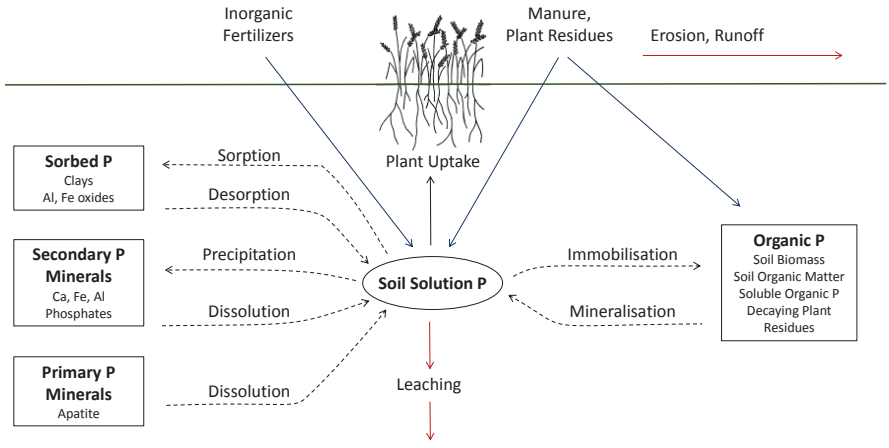

Figure 2. The soil phosphorus (P) cycle (adapted from Pierzynski *et al.*, 2005).

1.1.1 Sorption and desorption of phosphorus

The extent of sorption and desorption of P in soil depends on the concentration of phosphate or organic P in the soil solution. As mentioned above, P can be sorbed to surfaces of Fe and Al oxides and hydroxides in acid soils. This sorption can occur in two processes; the rapid surface reaction process of adsorption and relatively slow, and practically irreversible, absorption into porous material (van der Zee & van Riemsdijk, 1988). In the first step, P can be adsorbed to Al and Fe oxides through ligand exchange, where OH^- or H_2O is released and a phosphate surface complex is formed. In the second step, a hydrated oxide coating is formed around the adsorbed P, which makes it much less prone to desorption. In addition, P can be sorbed to positive edges of clay minerals and, in neutral to alkaline soils, also to the surfaces of $CaCO_3$, forming the sparingly soluble $Ca_3(PO_4)_2$.

Phosphorus can be released from the soil through desorption of P sorbed to surfaces, but also through mineralisation of organic P and dissolution of P minerals (Figure 2). However, the desorption process is much slower than sorption, due to the above-mentioned hydrated oxide coating around the phosphate ion.

The capacity of a soil to sorb P is often determined by formation of a sorption isotherm, in which the amount of P sorbed to the soil is shown as a function of P in the soil solution. However, determination of a sorption isotherm is time-consuming, and therefore Bache and Williams (1971) developed the P sorption index (PSI), in which one single high dose of P is added to the soil. With this procedure, it has been shown that the P sorption

capacity in most Swedish agricultural soils can be appropriately estimated (Börling *et al.*, 2001). The degree of P saturation (DPS), estimated by dividing soil P content by P sorption capacity (van der Zee *et al.*, 1987), shows how close a soil is to saturation. Several methods are used worldwide to estimate DPS. In Sweden, Fe, Al, and P extracted with ammonium lactate (AL) (Ulén, 2006) and the ratio of Olsen P to PSI (Börling *et al.*, 2004) have been shown to provide good estimates of DPS.

1.2 Phosphorus losses from agricultural land

Phosphorus can be transported from the field by surface runoff or via leaching through the soil. Studies have shown that P leaching can be extensive in many flat areas (van der Salm *et al.*, 2012; Algoazany *et al.*, 2007), and this is considered to be the main pathway for P losses in central Sweden (Ulén & Snäll, 2007). In *e.g.* structured clay soils with extended macropore flow, water with high P content can infiltrate and be transported through the soil via macropores more or less directly into tile drains and onwards to surface waters (Djodjic *et al.*, 1999). Almost half (49%) of the agricultural soils in Sweden are tile-drained (SCB, 2014), and much of the P that leaches through soil is transported to open ditches and other surface waters via subsurface drain flow.

Phosphorus can be lost from the soil as either dissolved or particulate P, both of which can include organic and inorganic forms of P. However, the relative proportions of dissolved and particulate P vary greatly depending on management practices, soil properties, transport pathways and hydrological features. Average losses of total P (TP) from Swedish agricultural land are about 0.4 kg ha^{-1} yr^{-1}, with an average of 45% as dissolved reactive P (DRP) (Ulén *et al.*, 2007). However, the variation in both TP losses (0.03-1.5 kg ha^{-1} yr^{-1}) and proportion of DRP (20-85%) is very large. In addition, spatial and temporal P loss variations are great, with high losses during intensive rainfall (Edwards & Owens, 1991) and snowmelt events (Ulén, 2003). Furthermore, most P losses can occur from a small part of the field, during a few intense storm events (Sharpley *et al.*, 1999). Pionke et al. (2000) found that 90% of the P losses in the Chesapeake Bay Basin, USA, originated from 10% of the catchment area, during a small window of time. It is therefore very important to identify the times when P losses are triggered and the 'hot-spots' where most P losses take place, and to specify the transport pathways (*i.e.* leaching and/or surface runoff), in order to apply cost-effective and properly positioned mitigation strategies to reduce P losses.

1.3 Importance of the subsoil

Leaching of P through the soil can occur either by rapid preferential flow or slow transport in the soil matrix. In soils with predominantly preferential flow, water transport occurs rapidly mainly through macropores. In these soils, only a small part of the subsoil and its sorbing area is in contact with the percolating water, and dissolved P may therefore be rapidly transported out from the soil (Djodjic, 2001). In soils with more uniform flow, where a major proportion of the pore volume contributes to water transport, P leaching may be high if the soil P content is high (due to natural enrichment or frequent P fertilisation) and/or the P sorption capacity is low. However, soils with uniform matrix flow and high P sorption capacity usually generate low P leaching, even when the topsoil P content is relatively high (Djodjic *et al.*, 2004).

Estimation of the risk of P losses from agricultural soils is crucial for enabling implementation of proper mitigation measures at farm scale, for the design of national mitigation strategies and for the development of good P indices and simulation models. However, due to lack of knowledge about P sorption and desorption in the subsoil, the actual P losses from soils are often difficult to predict. As mentioned previously, several studies have shown a lack of correlation between P concentrations in leaching waters and P content in the topsoil. In a Swedish lysimeter study conducted on 1 m long undisturbed columns of five different soils, Djodjic *et al.* (2004) reported that transport pathways of water through the soil profile and the extent to which P is bound and released in the subsoil had a greater impact on P leaching than P content in the topsoil. They also concluded that water and P from the topsoil bypassed the subsoil sorption sites in a clay soil where preferential flow dominated, resulting in high P leaching. In addition, water was transported more slowly through soils without preferential flow paths, enabling P in the soil solution to interact with the subsoil sorption sites, resulting in much lower P leaching. Similarly, on comparing a study on a 1 m long intact soil column from a Danish agricultural loamy field with a parallel topsoil study, Jensen *et al.* (1999) found that the subsoil had a large impact on P leaching. In a Finnish study, the highest P sorption capacity was found at approximately 30-70 cm depth, clearly affecting P leaching losses (Peltovuori, 2007). The importance of subsoil properties for P leaching has also been pointed out by *e.g.* Sinaj *et al.* (2002), Nelson *et al.* (2005) and Liu *et al.* (2012b). Although several studies have pointed out the importance of subsoil properties for P leaching, none has tried to quantify the effect of the subsoil *per se* on P leaching.

1.4 Mitigation of phosphorus losses

In order to implement suitable mitigation strategies for P losses, it is highly important to be aware of how and where P is lost from the soil. In reducing P losses from arable land, focus can be either on reducing release of P from soil and fertilisers or preventing transport of P from the soil (or both). It is important for livestock farms to follow tailored feed recommendations and to practise appropriate manure management, *i.e.* to have sufficient storage capacity, to apply at the recommended time and rate, and to incorporate immediately after spreading on clay soils (*e.g.* Liu *et al.*, 2012a; Glaesner *et al.*, 2011).

Losses of P through erosion and surface runoff can be reduced by using buffer zones (Bergström *et al.*, 2007). In addition, improving soil structure and aggregate stability by adding some kind of reactive material to the soil may decrease both the release and the losses of P from the soil. More than 100 different types of materials that could be used as soil amendments have been tested in the laboratory for their P sorption capacity (King *et al.*, 2015b). Structure liming, in which quicklime (CaO) or hydrated lime ($Ca(OH)_2$) is incorporated into clay topsoil, is officially recommended in Sweden to reduce P losses from clay soils (SBA, 2014). While this method was shown to significantly reduce P leaching from two field plots with clay soil in a study by Ulén & Etana (2014), incorporating lime into the topsoil may also decrease the amount of DRP available for crop uptake (Curtin & Syers, 2001). The balance between bioavailability and the risk of losses is therefore an important issue.

In addition, P can be captured beyond the field boundary by using *e.g.* gypsum filters (Bryant *et al.*, 2012) or constructed wetlands (Kynkäänniemi *et al.*, 2013) as complementary mitigation options.

2 Objectives

The overall objective of this thesis was to study the impact of subsoil on P leaching from agricultural soils and to identify important subsoil properties that could be used for risk assessment of P leaching through soil. This type of information is crucial when deciding proper mitigation measures for P losses at farm scale, when designing mitigation strategies in national water quality management and when developing different types of models, *e.g.* risk index models and national load calculations. Specific objectives were to:

I Study P leaching from some Swedish agricultural soils in relation to soil characteristics of the topsoil and subsoil and, in particular: (i) determine P content, P binding capacity and P release in the topsoil and subsoil; (ii) examine variations in P leaching from these soils; and (iii) discuss the influence of extractable soil P concentration and relevant topsoil and subsoil characteristics on P leaching (Paper I).

II Determine whether subsoils of some Swedish agricultural soils act as a source or sink for P and thereby affect leaching and, in particular: (i) study temporal and soil-dependent variations in P leaching from soils with contrasting texture and chemical characteristics, with and without the topsoil, and assess the causes of possible differences; (ii) quantify the contribution of the subsoil to total P leaching in these soils; and thereby (iii) determine whether the subsoil has the potential to act as a source or sink for P leaching from the soils (Paper II).

III Investigate whether placing lime on the subsoil of the selected soils could reduce P leaching in particulate and/or dissolved form (Paper III).

The main hypotheses were that subsoils can act as both a source and a sink for P and thereby have a major impact on P leaching, and that liming of the subsoil can reduce P leaching.

3 Soil description and study method

Intact soil columns (lysimeters) were used in Papers I-III to study the impact of subsoil features on P leaching and the effect of lime placement on subsoil as an option to reduce P leaching.

3.1 Site and soil description

Four agricultural soils in southern Sweden (Mellby, Nåntuna, Bornsjön, Lanna) were used in the studies (Figure 3). The soils were chosen to represent different physical and chemical properties. The Mellby and Nåntuna soils are sandy soils, with high concentrations of iron precipitates present in the subsoil of the Mellby soil. Bornsjön and Lanna are clay soils, with presumed high calcium carbonate concentration in the Lanna soil. Furthermore, for three of the soils (Mellby, Lanna and Bornsjön), long-term data on P leaching are available, enabling comparisons with P leaching data at field-scale.

Figure 3. Map of southern Sweden showing locations where soil columns were collected.

3.2 Lysimeter collection and management

Nine intact soil columns (three with topsoil and subsoil, six with only subsoil) were collected at each site in autumn 2009 by using a drilling method where a carved-out soil column is gently pushed into a polyvinyl chloride pipe (Figure

4), as described by Persson and Bergström (1991). To collect subsoil lysimeters, topsoil was first manually excavated before drilling started directly on the subsoil. Diameter of the final soil columns was 0.295 m and the length was 1.05 m (full-length lysimeters) and 0.77 m (subsoil lysimeters) (Figure 5). After collection and preparation, the gravity-drained lysimeters were placed in an outdoor lysimeter station described by Bergström and Johansson (1991). A stainless steel mesh was placed on top of the subsoil lysimeters to protect the surface from heavy rainfall.

No crop was grown in the soil columns in order to avoid interference from crop uptake of water and P during the experimental period. Fertiliser ($(NH_4)H_2PO_4$) at a rate equivalent to 22 kg P ha^{-1} was added once in April 2011 to all lysimeters to simulate common Swedish agricultural practice and to study possible effects of fertilisation on P leaching. Drainage volumes were measured continuously from each soil column over three years (1 Sept. 2010 to 31 Aug. 2013). Water samples were collected on a weekly basis or after each major drain flow event, and TP and DRP in leachate were analysed colorimetrically according to European Committee for Standardisation methods (ECS, 1996). Particulate P (PP) was defined as the difference between TP in unfiltered and filtered samples (filter size: 0.2 µm), and the difference between TP and DRP+PP was defined as residual P. The residual P fraction was not further analysed.

Figure 4. Collection of lysimeters with topsoil and subsoil (left and centre) and without topsoil (right). Photo: Helena Andersson.

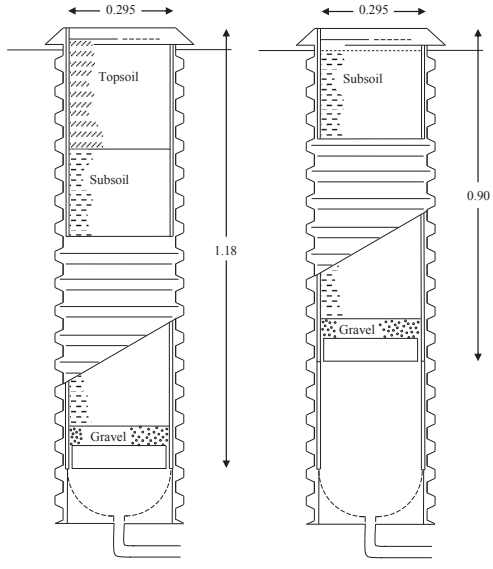

Figure 5. Lysimeters with (left) topsoil and subsoil and (right) only subsoil, placed in below ground pipes. Adapted from Bergström and Johansson (1991).

Three of the soils (Nåntuna, Lanna and Bornsjön) were used to test whether placing lime on the subsoil could reduce P leaching in particulate and/or dissolved form. Due to high P sorption capacity in the Mellby sand subsoil, no further mitigation options for P leaching from that soil were considered necessary.

In November 2010, the uppermost 0.01 m of three subsoil lysimeters of each soil was manually removed. The excavated soil was then thoroughly mixed with CaO at a rate equivalent to 5 ton ha^{-1} before being replaced on the respective lysimeter.

4 Subsoil – source or sink for phosphorus leaching

Although several previous studies have found significant correlations between high topsoil P content and high P leaching, others have concluded that topsoil properties alone are insufficient for P leaching predictions for many soils. For example, in a study using 1-m undisturbed soil columns of the same type as used in my studies, Djodjic *et al.* (2004) found no significant correlation between topsoil P content (Olsen P and P-AL) and P leaching from five soils with varying textural composition. Similarly, Sinaj *et al.* (2002) studied two loamy soils using intact lysimeters and found that high P sorption capacity in the subsoil retained large amounts of P mobilised in the topsoil. In these previous studies, it was concluded that subsoil properties are of great importance for P leaching.

The work presented in Papers I and II showed that subsoil properties (P content, P sorption capacity and degree of P saturation) can be of great importance for P leaching from both fine-textured soils with structural features and unstructured, coarse-textured soils. Figure 6 illustrates the leaching load of DRP, PP and residual P (defined as the difference between TP and DRP+PP) from all soils, with and without topsoil, as reported in Paper II. Mean annual DRP leaching load was lower from subsoil lysimeters than from full-length lysimeters for all soils, whereas the opposite was found for PP leaching from the Mellby sand, Nåntuna sand and Lanna clay. This might be explained by direct exposure of the subsoil to heavy precipitation and freezing/thawing processes, contributing to release of particles from the soil matrix. In addition, colloidal aggregates may have been destabilised as rainwater with lower ionic strength than soil water hit the subsoil surface, resulting in increased PP losses (*e.g.* Ilg *et al.*, 2005; DeNovio *et al.*, 2004).

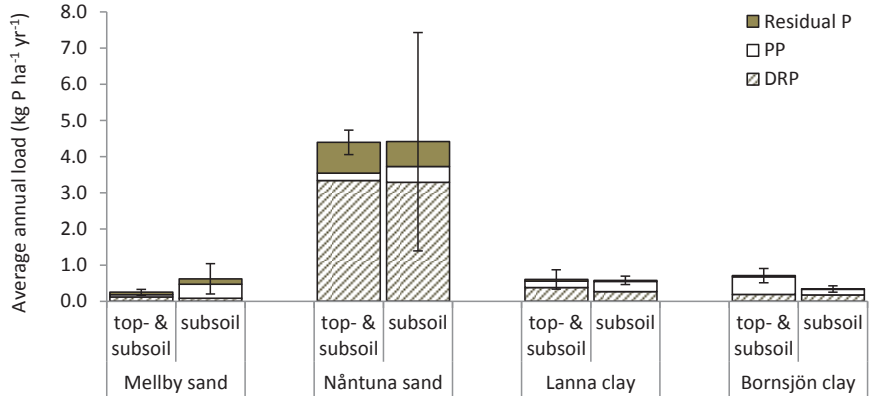

Figure 6. Average annual leaching load of dissolved reactive phosphorus (DRP), particulate phosphorus (PP) and residual phosphorus (defined as the difference between TP and DRP+PP) from full-length and subsoil lysimeters of the Mellby sand, Nåntuna sand, Lanna clay and Bornsjön clay, 1 Sept. 2010 to 31 Aug. 2013. Error bars show standard deviation for total phosphorus (TP).

In Sweden, P leaching is mainly considered a problem on soils with high clay content (Bergström *et al.*, 2007). However, the results in Papers I and II show that sandy soils can also be a substantial hot-spot for P leaching. The Nåntuna sand had a high P content in both topsoil and subsoil, low P sorption capacity in the subsoil and very high P leaching. In addition, the variation within subsoil lysimeters was very large, with average annual TP leaching load of 1.9-7.8 kg ha^{-1} yr^{-1}. Lysimeters with high P leaching were collected close to each other and hence had high P leaching load regardless of treatment (the lysimeters were randomly chosen for lime addition).

4.1 Forms of phosphorus in leachate

Macropore flow has been reported to be the main pathway for water and solutes in the Lanna clay (Bergström & Shirmohammadi, 1999). Non-equilibrium flow behaviour has also been suggested as a common flow pattern in the Bornsjön clay (Ulén *et al.*, 2014). In clay soils with preferential flow paths such as macropores, there may be a direct connection between the soil surface and drainage pipes, and these soils are therefore often associated with greater nutrient losses after *e.g.* fertiliser application than soils without macropore flow (*e.g.* Jarvis, 2007; Simard *et al.*, 2000; Singh & Kanwar, 1991). In addition, in soils with macropore flow, the proportion of PP is often

greater than in soils with matrix flow (Uusitalo *et al.*, 2001). Bottcher *et al.* (1981) reported that over a three-year period, 70% of TP losses from a monitored tile-drained field were in the form of PP. They also reported that PP leaching increased following fertilisation. However, P leaching did not increase in any of the soils studied in Papers I and II after P fertilisation in spring 2011. Despite previous findings by Bergström & Shirmohammadi (1999) and Ulén *et al.* (2014), this may indicate that preferential flow was limited in the clay soil lysimeters included and that P already present in the soil overshadowed the effect on leaching of a single P fertiliser application. In addition, one single application of a relatively low dose such as used in this study (22 kg P ha^{-1}) has previously been shown not to result in increased P losses (Djodjic & Mattsson, 2013).

In Papers I and II in this thesis, the proportion of PP in leachate in the full-length lysimeters was low for the Nåntuna sand (6 and 5%), moderate for the Mellby sand (8 and 25%) and the Lanna clay (21 and 26%), and high for the Bornsjön clay (63 and 70%). These results confirm findings by Svanbäck *et al.* (2014), who reported PP proportions in leachate from field plots at the Bornsjön clay of 85% of TP. Similarly, Djodjic *et al.* (1999) reported PP concentrations in leachate of on average 20% of TP from 1-m high undisturbed soil columns of Lanna clay. Djodjic *et al.* (1999) and Papers I and II both report lower proportions of PP than previously measured in a field plot study conducted on the Lanna clay (Aronsson *et al.*, 2011). In that study, DRP proportions of 31% and 18% of TP, respectively, were reported during two two-year periods. The lower PP proportion in the lysimeter studies might be due to lack of continuity of macropores in this type of lysimeter installation. Similarly, reductions in leaching of both DRP and PP have been reported by Geohring *et al.* (2001) after disruption of macropores through ploughing. In addition, drain backfill may release more PP than an undisturbed soil column, which may also explain the lower PP proportions in the lysimeters compared with field measurements. Although macropore flow has been reported as a common flow pattern in both the Lanna clay and the Bornsjön clay, it should be noted that determination of the degree of macropore flow in a soil is difficult, and was not done on any of the soils included in this thesis. Still, rapid transport of solutes in soil is commonly interpreted as being caused by macropore flow.

Phosphorus leaching, in both particulate and dissolved form, has often been observed to increase greatly during high flow events (*e.g.* Dils & Heathwaite, 1999; Ulén & Persson, 1999; Sims *et al.*, 1998), and is often high during cooler, wetter winter months than in drier periods (*e.g.* King *et al.*, 2015a; Macrae *et al.*, 2007). Concentrations of PP in leachate were observed to

increase in the Lanna clay subsoil lysimeters and the Bornsjön clay full-length lysimeters during autumn and winter, when drain flow was high (Paper II). Similarly, Heathwaite & Dils (2000) and Chapman *et al.* (2001) reported increased subsurface PP concentrations in winter. In Sweden, PP often dominates in tile drains during high flow events on soils with macropore flow (Ulén & Jakobsson, 2005). However, PP concentrations in drainage also increased greatly at snowmelt in the subsoil lysimeters of both sandy soils studied. This can be attributed to direct exposure of the subsoil to freezing/thawing processes, or to destabilisation of aggregates by rainwater with lower ionic strength than soil water hitting the subsoil surface, as mentioned previously.

4.2 Subsoil contribution to total phosphorus leaching

Leaching loads of DRP were much lower in both full-length and subsoil lysimeters of the Mellby sand (0.12 and 0.08 kg ha^{-1} yr^{-1}, respectively) than the Nåntuna sand (3.33 and 3.29 kg ha^{-1} yr^{-1}, respectively). In addition, DRP leaching load from subsoil lysimeters compared with full-length lysimeters was 99% for the Nåntuna sand and 70% for the Mellby sand (Paper II). These results show that the subsoil of the Nåntuna sand acted as a source for P leaching, while the Mellby sand subsoil acted as a sink. The reason for this was the high subsoil P content and low P sorption capacity, measured as P sorption index (PSI), in the Nåntuna sand (Table 1), as presented in Paper I. The P sorption capacity in the Mellby subsoil was very high, which caused it to function as a sink for P leaching. These results are in line with findings by Sinaj *et al.* (2002) of very high P content in the topsoil and high P sorption capacity in the subsoil resulting in low P leaching. In addition, Djodjic *et al*. (2004) reported low P leaching from a sandy soil despite high P application, due to high P sorption capacity in the subsoil.

Moreover, on comparing results from topsoil studies with the results presented in this thesis, the importance of subsoil properties is revealed. Liu *et al.* (2012c) measured P leaching from intact topsoil columns of Mellby sand and found TP concentrations in leachate of 0.30-0.57 mg L^{-1}, which is much higher than reported for Mellby full-length lysimeters in Paper II in this thesis (0.07-0.12 mg L^{-1}). Similarly, Riddle & Bergström (2013) used the same type of intact topsoil lysimeters and studied P leaching from the Nåntuna sand after freezing and thawing cycles. They found average TP leaching concentrations before any freezing events ranging from 0.37 to 0.48 mg L^{-1}, which is much lower than the average annual TP concentrations from the Nåntuna full-length lysimeters in Paper II (1.12-1.23 mg L^{-1}).

Table 1. *Selected chemical and physical properties of the four soils used in Papers I-III in this thesis.*

Soil	Layer	Texture	Clay (%)	pH	Olsen P (mg kg^{-1})	P-AL (mg kg^{-1})	PSI (mmol kg^{-1})	Olsen P/PSI (%)
Mellby	Topsoil	Sand	7	6.0	84.4	261	4.2	65
	Subsoil	Sand	1	5.6	8.0	14	3.7	7
Nåntuna	Topsoil	Loamy sand	10	7.2	26.5	145	2.3	40
	Subsoil	Sand	4	7.6	18.7	61	1.3	49
Lanna	Topsoil	Silty clay	44	6.2	8.6	32	5.6	5
	Subsoil	Clay	59	7.0	<4.0	139	6.9	2
Bornsjön	Topsoil	Clay	60	6.1	17.3	38	7.5	8
	Subsoil	Clay	57	6.1	10.1	17	8.3	4

PSI: phosphorus sorption index

It is important to be aware of subsoil properties, not only for P loss risk estimation, but also for development and parameterisation of simulation models used for estimation of P losses at field scale, catchment scale and national scale (Radcliffe *et al.*, 2015), and for development and implementation of good, cost-effective mitigation measures. By including only topsoil properties, any simulation model in the world would suggest that P leaching would be more problematic in the Mellby sand than in the Nåntuna sand due to the higher P content in the former (Table 1), and that very powerful mitigation options would be needed at the Mellby site. However, due to low P leaching from the entire profile (as a result of high subsoil P sorption capacity), P leaching reduction measures can be considered unnecessary on the Mellby sand, whereas very powerful mitigation options for P leaching are needed on the Nåntuna sand. Hence, if only topsoil properties and P leaching from the topsoil were studied, mitigation options would have been applied in the Mellby field even though the results presented in this thesis suggest that this is unnecessary.

Djodjic (2015) made a compilation of data from more than 12 000 Swedish agricultural topsoils and found that the average content of Fe-AL and Al-AL was 50 and 40 mg 100 g^{-1}, respectively. In this thesis, Fe and Al extracted with ammonium lactate (Fe-AL and Al-AL) amounted to 45 and 44 mg 100 g^{-1} in the Mellby sand topsoil and 18 and 11 mg 100 g^{-1} in the Nåntuna sand topsoil. Hence, the Nåntuna sand topsoil had a much lower content of both Al and Fe than most Swedish agricultural topsoils, which also confirms that this soil has low P sorption capacity. However, no similar data for the corresponding subsoil properties are available on a national scale, and therefore similar comparisons for the subsoil data can not be conducted.

Although preferential flow has been suggested to be a common flow pattern in the Bornsjön clay (Ulén *et al.*, 2014), it should be noted that no visible macropores could be found in deeper layers when collecting lysimeters at the Bornsjön site. In addition, the Bornsjön clay subsoil lysimeters were often ponded after heavy rainfall during the study period, indicating lack of macropore flow in these lysimeters. This suggests that the extent of macropores varies over space and time in the Bornsjön clay. The increased contact time between P in the soil solution and the sorption sites, in addition to the slightly higher P sorption capacity (Table 1), might explain the tendency (not significant, $P>0.05$) for lower DRP leaching load from full-length lysimeters of the Bornsjön clay (0.19 kg ha^{-1} yr^{-1}) than from the Lanna clay (0.38 kg ha^{-1} yr^{-1}). Even though the Lanna clay was chosen due to its presumed calcium carbonate content, none was found in the chemical analyses (Paper I).

Leaching load of DRP from subsoil lysimeters was 70% of that from full-length lysimeters for the Lanna clay, whereas it was 94% for the Bornsjön clay (Paper II). The higher relative contribution to total DRP leaching of the Bornsjön subsoil than the Lanna subsoil can be attributed to higher P content at depth (70-100 cm) in the Bornsjön clay (Paper I). However, it should be kept in mind that DRP leaching was much lower from the Bornsjön clay subsoil (0.17 kg ha^{-1} yr^{-1}) than from the Lanna clay subsoil (0.27 kg ha^{-1} yr^{-1}). So even though the Bornsjön subsoil contributed a larger proportion to total DRP leaching load than the Lanna clay, leaching was low from that soil.

4.3 Subsoil properties for phosphorus leaching assessment

In Paper II, DRP leaching increased with increasing Olsen P and DPS in the subsoil in both full-length and subsoil lysimeters (Figure 7a and b). However, the relationships in full-length profiles were not statistically significant, which might be attributed to the small number of measurements and the highly clustered data (caused by high P leaching load from the Nåntuna sand). A similar relationship has been found between DRP leaching from 12 Swedish fields with varying P content and DPS (estimated as the relationship between Fe+Al to P, extracted in ammonium lactate) in sandy subsoils and clay topsoils (Ulén, 2006). In addition, DRP leaching in Paper II decreased with increasing PSI in both topsoil and subsoil (Figure 7c). In a Finnish study, the highest P sorption capacity of four cultivated soils (two fine-textured and two coarse-textured) was found below the topsoil, and it was concluded that this could clearly affect P leaching from those soils (Peltovuori, 2007). Despite the lack of significant relationships between subsoil Olsen P and DPS and DRP in full-length lysimeters, the results presented in Paper II still indicate the importance

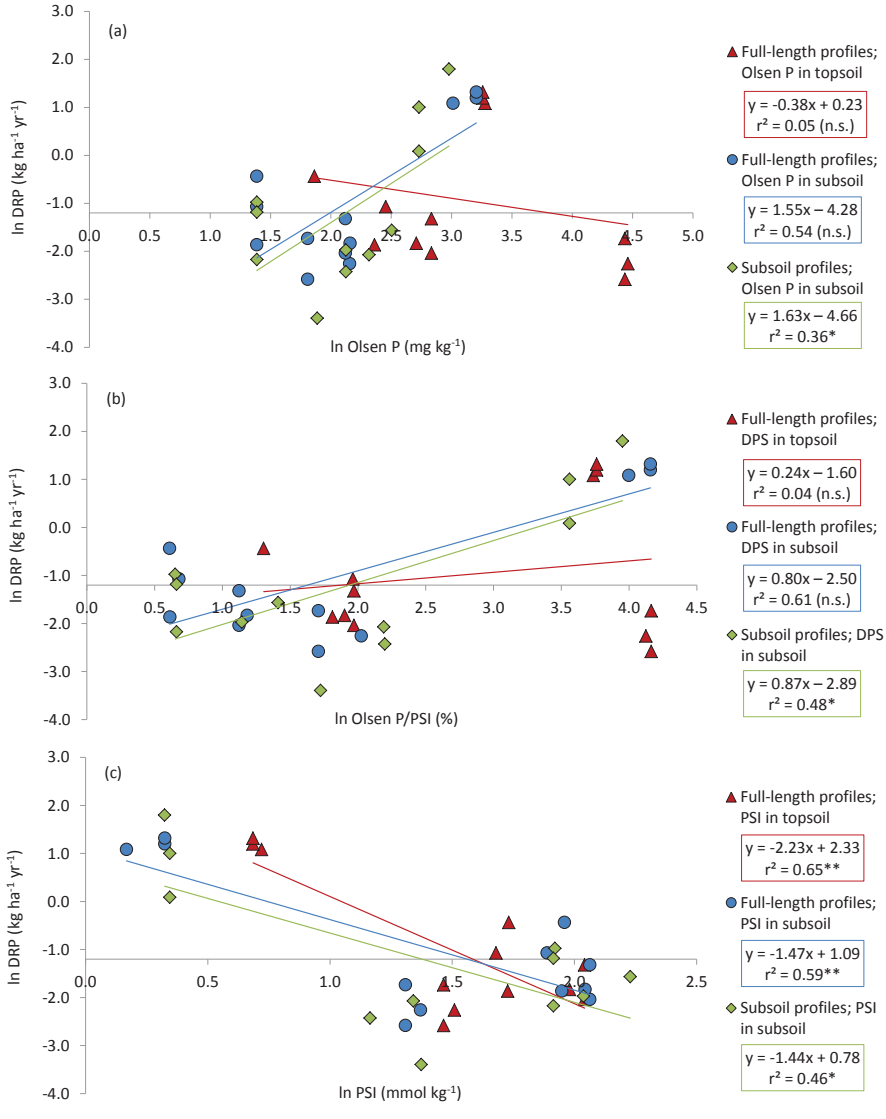

Figure 7. Relationship between mean annual leaching load of dissolved reactive phosphorus (DRP) and (a) Olsen P, (b) degree of phosphorus saturation (Olsen P/PSI), and (c) phosphorus sorption index (PSI) in topsoil and subsoil. *Significant at P<0.05, **significant at P<0.01.

of subsoil properties for DRP leaching. This confirms findings by Djodjic *et al.* (2004) of no relationship between Olsen P and DPS in the topsoil and P leaching from the same type of full-length lysimeters as described in this

thesis. Thus, these results suggest that determination of topsoil properties is insufficient for predicting the risk of P leaching from many soils and that subsoil properties such as Olsen P, DPS or PSI should be included in P leaching risk assessments at both farm and national scale. Phosphorus extracted with ammonium lactate (P-AL) is commonly used for estimation of soil P content in Sweden. However, in the Lanna clay P-AL increased with depth, whereas the Olsen P value decreased (Table 1). The strongly acid (pH 3.75) extraction with ammonium lactate can dissolve P bound to calcium (Ca). Since no Ca-carbonate was found in the analyses performed (Paper I), the results may indicate the presence of Ca-phosphates in the soil. In a previous study on a similar clay soil located close to the Lanna field, P was found to be bound to Ca complexes, with increasing P concentrations with increasing soil depth (Ulén & Snäll, 2007). Since P in these forms is less soluble under neutral and alkaline conditions, the P-AL value may therefore be an overestimation of plant-available P in the Lanna clay.

It should be noted that even though the P sorption capacity is often higher in fine-textured soils than in sandy soils, preferential flow pathways are an important feature of subsurface P losses in the former. Djodjic *et al.* (2004) found high P leaching losses from a clay soil with low DPS, which meant that P sorption sites were bypassed due to preferential flow. Therefore, chemical properties are usually insufficient for estimating the risk of P leaching in clay soils (King *et al.*, 2015b).

5 Subsoil liming for phosphorus leaching reduction

When adding lime to soil, cation exchange takes place, followed by adsorption of calcium to clay minerals and flocculation of clay particles (Bell, 1996). This leads in turn to improved soil stability, porosity and aggregate strength (Haynes & Naidu, 1998). The slower cementing pozzolanic reaction between CaO, silica and aluminium increases the soil strength (Locat *et al.*, 1990). Increased soil stability is therefore often associated with reduced losses of P, especially PP.

As shown in Paper III, mean annual leaching losses of PP were significantly lower from lysimeters with lime added than from lysimeters without lime for the Lanna clay (0.14 kg ha^{-1} yr^{-1} lower, 49% reduction) and the Bornsjön clay (0.08 kg ha^{-1} yr^{-1} lower, 51% reduction). A comparison of the average annual P load, measured as DRP, PP and residual P (defined as the difference between TP and DRP+PP), from lysimeters with and without lime addition of the three soils included in the study is shown in Figure 8. Adding lime to the upper 0.01 m layer of the subsoil resulted in lower drainage outflow peaks at snowmelt in 2012 and 2013. In addition, PP concentrations over time were more uniform in the limed lysimeters than in those without lime. These results are in line with findings by Ulén *et al.* (2012) that lime addition improves soil aggregate stability, and by Ulén & Etana (2014), who reported significantly lower PP leaching from the Bornsjön field when structure lime was added to the topsoil.

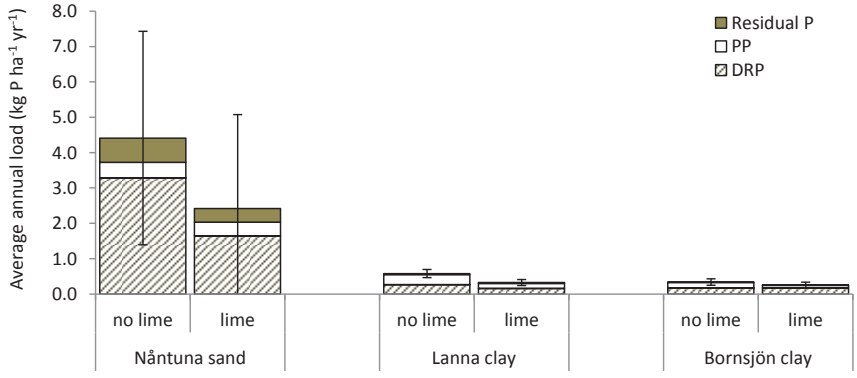

Figure 8. Average annual P leaching load of dissolved reactive phosphorus (DRP), particulate phosphorus (PP) and residual phosphorus (defined as the difference between TP and DRP+PP) from the Nåntuna sand, Lanna clay and Bornsjön clay in lysimeters with and without lime, 1 Sept. 2010 to 31 Aug. 2013. Error bars show standard deviations for total phosphorus (TP).

Due to the extremely large P losses observed for the sandy Nåntuna soil, lime was also added to the subsoil of that soil, even though liming is not known to improve the structure of soils with a low clay content (Berglund, 1971). It was found that average annual leaching load of both PP and DRP from the sandy soil was lower from the lysimeters with lime addition than from those without. However, these reductions were not statistically significant due to extremely high variation in P leaching between lysimeters. In addition, due to very high P leaching from the subsoil, as a result of high P content and low P sorption capacity, the subsoil clearly acted as a source for P leaching. Placing lime on top of the subsoil to reduce P leaching is therefore inefficient and could not be recommended on this soil. Instead, mitigation measures implemented around tile drains (Groenenberg *et al.*, 2013) or after the edge of the field (*e.g.* Kynkäänniemi *et al.*, 2013; Bryant *et al.*, 2012) might be preferable on sandy soils with high P content and low P sorption capacity in the subsoil. It is highly important to identify critical source areas, *i.e.* soils or fields with high P leaching load (Gburek *et al.*, 2000), in order to reduce the environmental impact on freshwater bodies and, in northern Europe, the Baltic Sea. The Nåntuna sand is located close to the river Fyrisån, which discharges at a point approximately 3 km downstream from the study field into Ekoln, a narrow inlet of Lake Mälaren, which occasionally has outbreaks of algal blooms (Fölster *et al.*, 2014). Since the Nåntuna soil can be considered an important 'hot spot' for P losses, there is a great need for powerful mitigation strategies to reduce P losses from the field.

In addition, leaching of PP increased in the limed Nåntuna lysimeters after approximately one pore volume had been drained after fertilisation in spring 2011 (Paper III). However, the reason for the increase in PP concentrations was not investigated in detail. An increase in P leaching due to P fertilisation was not noted for any of the limed clay soil lysimeters. As mentioned previously, this might indicate the limitation of preferential flow in the clay soil lysimeters used in this study and that P already present in the soil overshadowed the effect on leaching of one single P fertiliser application.

5.1 Why subsoil liming?

As mentioned previously, incorporation of quicklime (CaO) or hydrated lime ($Ca(OH)_2$) into clay topsoils has been shown to significantly reduce P leaching in field plots of two Swedish clay soils (Ulén & Etana, 2014). Several previous studies have shown that adding lime to soil increases or does not affect the plant availability of P (*e.g.* Holford *et al.*, 1994; Haynes, 1982). However, others have found that adding lime to topsoil may reduce the amount of plant-available P (Murphy & Stevens, 2010; Curtin & Syers, 2001). Furthermore, to ensure good infiltration and crop growth, this type of treatment has to be performed during appropriate weather conditions and when the soil is dry. It should be followed by one or several incorporations to avoid 'cementing effects' (SBA, 2014). In the experiment described in Paper III, CaO was incorporated into the uppermost 0.01 m of the subsoils which were not expected to act as a sink for P leaching (*i.e.* Nåntuna sand, Lanna clay and Bornsjön clay). The objective of this deep placement of lime (*i.e.* below the topsoil) was to create a filter for fertiliser P and P mobilised in the topsoil, without risking reducing P availability for plant roots in the topsoil. However, since PP leaching losses were significantly reduced in the clay soils, there is reason to believe that this amendment also improved the soil structure and thereby reduced losses of particles. In addition, to place lime on the subsoil might be less weather-dependent than topsoil liming. Hence, on clay soils with good topsoil structure and high P leaching, lime placement on the subsoil could be a useful mitigation strategy for P leaching.

However, adding lime under the topsoil can be laborious and expensive. Although deep placement of lime to reduce P leaching has not been tested in a field setting, there are techniques available that could be used, which involve deep cultivation (Spoor, 2006) and incorporation of lime by slotting (Blackwell *et al.*, 1990). However, to reach the full potential of this method as a filter for percolating water, lime should be evenly distributed on the subsoil. Thus, the techniques for deep incorporation need to be further developed. In addition, the

actual need for deep placement of lime has to be thoroughly investigated before implementation, to ensure that the strategy is cost-effective.

6 Evaluation of the study method

The risk of side-wall flow is often discussed when presenting results from lysimeter studies. In a tracer study with Acid red on the Mellby sand and the Lanna clay using the same type of lysimeters as those in Papers I-III (Bergström & Shirmohammadi, 1999) and in a study using ^{36}Cl and H_3O^+ on lysimeters containing Nåntuna sand and Lanna clay (Bergström *et al.*, 1994), no signs of side-wall flow were observed. In other words, side-wall flow does not seem to be a major problem with this type of lysimeter.

Previous P leaching studies conducted over six years on tile-drained plots of three of the soils used in my studies reported similar P leaching loads as those presented in Paper II, *i.e.* average TP leaching of 0.23 kg ha^{-1} yr^{-1} for the Mellby sand field (Torstensson *et al.*, 2006), 0.81 kg ha^{-1} yr^{-1} for the Lanna clay field (Aronsson *et al.*, 2007) and 0.97 kg ha^{-1} yr^{-1} for the Bornsjön clay field (Svanbäck *et al.*, 2014). This indicates that lysimeter results provide a good estimate of P leaching from the soils used in this thesis work. Unfortunately, no field measurements of P leaching from the Nåntuna sand were available. However, there are some major differences between lysimeters and field plots that should be borne in mind. No crop was grown in the lysimeters used in these experiments, resulting in higher drainage and probably also higher P leaching than if a crop had been present. However, the effect of a crop on P leaching may be difficult to assess, and keeping the soil bare therefore improves the possibilities to estimate the effect of various soil properties on P leaching. In addition, drain bypass can occur in tile-drained soils, which could reduce drainage volumes considerably (Bergström, 1987). Moreover, due to impeding layers below the topsoil, in a field setting there may also be a risk of lateral water flow moving directly from the topsoil into drain backfill and drainage pipes in tile-drained soils (Øygarden *et al.*, 1997; Bergström & Johnsson, 1988). This would result in less water flow through the soil profile between the tile drains. On clay soils, there is also a risk of surface runoff. However, all water reaching the soil surface in lysimeters that does not

evaporate infiltrates into the soil. The main objective of the work in this thesis was to study the impact of various soil properties on P leaching. Hence, using undisturbed lysimeters without any crop, instead of *e.g.* tile-drained field plots, for this type of study on investigating the influence of soil properties on P leaching is preferable.

Due to the free gravity drainage in the lysimeters used in this thesis, a water-saturated zone must be formed at the lysimeter base before drainage can occur. This may contribute to higher moisture content in a lysimeter than in a field of the same soil. However, since the soil column length of the full-length lysimeters was approximately 1 m, which is a common tile drainage depth in Sweden, field conditions could be considered to be quite well simulated in the lysimeter studies.

The larger PP leaching load from subsoil lysimeters than from full-length lysimeters for the sandy soils and the Lanna clay may have been due to direct exposure of the subsoil to precipitation and freezing/thawing processes, as mentioned above. The stainless steel mesh placed on the surface of the subsoil lysimeters might not have provided enough protection of the soil surface. In addition, rainwater has lower ionic strength than soil water and application of rainwater directly to the subsoil may therefore have caused destabilisation of colloidal aggregates, resulting in increased losses of PP (*e.g.* Ilg *et al.*, 2005; DeNovio *et al.*, 2004).

Since topsoil was excluded from the liming study presented in Paper III, conclusions could not be drawn regarding the effect of liming on P leaching and P sorption in the topsoil. Hence, the work presented in Paper III does not represent a real-case scenario, but instead shows the potential of the subsoil to reduce P leaching due to liming on top of the subsoil. To enable evaluation of using subsoil liming as a filter for P in water percolating from the topsoil, the topsoils should have been included in the study.

When using lysimeters, only a small fraction of the field is studied. Since soil physical and chemical properties may vary greatly within a field, lysimeters may demonstrate different results compared with field studies. In the experiments described in this thesis, this was true for the Nåntuna sand lysimeters, in which the variation in P leaching within the lysimeters was very large. This was somewhat surprising, since large variations are normally more common in clay soil replicates than in sand replicates due to the more heterogeneous flow pattern in most clay soils (Bergström & Shirmohammadi, 1999). In addition, water ponding was observed on some of the Bornsjön clay subsoil lysimeters, which may indicate that the continuity of macropores was lower in the soil columns used than in the field. The solution to this problem

would be to use many and larger lysimeters of each treatment, which is usually not possible for economic reasons.

The soils in this study were chosen due to their presumed differing chemical and physical properties and expected flow paths. However, the extent of macropore flow was not explicitly tested within this project. In addition, the Lanna clay was intended to represent a clay soil from an area with high P sorption capacity due to presence of calcium carbonate in the subsoil. However, no calcium carbonate was found in the chemical analyses performed in this study (Paper I). The presumed difference in P sorption capacity between the two clay soils used was hence not apparent. In fact, the presence of Fe and the total P sorption capacity (measured as PSI) were slightly higher in the Bornsjön clay than in the Lanna clay. Chemical analyses of the soils should therefore have been conducted before lysimeter collection, to ensure the use of soils with both high and low P sorption capacity. In addition, clay soils with well-documented high P leaching loads should have been used in the experiments.

7 Conclusions

The results presented in this thesis show that subsoils can act as both a source and sink for P leaching. The subsoil can thereby be critical for the extent of P leaching and can have an impact on the design of mitigation strategies for P leaching reductions and how they should be positioned.

Leaching of P was much higher in the sandy soil with moderate topsoil P content (Nåntuna) than in the sandy soil with high topsoil P content (Mellby). The reason was high subsoil P content and low P sorption capacity in the Nåntuna sand and high subsoil P sorption capacity in the Mellby sand. Hence, on soils with low subsoil P sorption capacity, P leaching is dependent on P release in the soil, or on P added with fertilisers, manure or other amendments. Powerful strategies for reducing P leaching are needed on these soils. However, on soils with high subsoil P sorption capacity, mitigation options for P leaching are not necessary in the short-term unless the sorption capacity is exceeded. It is still important to avoid heavy fertilisation of these soils for longer periods, since this may cause DPS in the subsoil to reach levels where P leaching starts to increase. Olsen P and DPS in the subsoil and PSI in both topsoil and subsoil were found to be significantly correlated to P leaching, indicating that these properties could be used for estimating P leaching from soil. However, on soils with preferential flow in the subsoil (although not explicitly studied in the experiments presented in this thesis), P in soil water may be transported rapidly through the soil, without interacting with the sorption sites. Thus, to enable implementation of proper and cost-effective mitigation strategies for P leaching reductions, the focus should always be on chemical and physical properties in both topsoil and subsoil.

Addition of lime to the subsoil significantly reduced PP leaching from both clay subsoils studied, suggesting that this could be an effective method for reducing P leaching from clay soils without the risk of affecting plant availability of P in the topsoil. However, due to low clay content, lime addition

did not decrease P leaching from the sandy subsoil. This soil had a very high P content and low P sorption capacity in the subsoil, and hence also very high P leaching losses. Mitigation measures on these types of soils should be applied at the edge of the field instead of in the soil, in order to effectively reduce P losses from the field.

8 Recommendations and future research

This thesis demonstrated that subsoil properties can be of great importance for P leaching. By only focusing on topsoil properties, mitigation measures for P leaching reductions would probably be applied in fields with high topsoil P content. However, if the subsoil has high P sorption capacity, P leaching from the entire profile may be lower than expected from studying P content or P leaching from the topsoil only. It is highly important to identify subsoils which act as a source for P leaching, since these 'hot-spots' may contribute a large proportion of P losses to surrounding recipients. By measuring subsoil P content and P sorption capacity, it can be determined whether the subsoil acts as a source or a sink for P leaching. Based on that knowledge, proper mitigation strategies for P losses can be developed and implemented.

In a soil with preferential flow, P may be transported at high velocity through the profile, preventing any sorption in the subsoil. Therefore, although subsoil properties were shown to be well correlated to P leaching in this thesis, the extent of preferential flow in a soil must be taken into account when assessing P leaching on clay soils. In order to achieve maximum cost-efficiency of the mitigation strategies applied, the chemical and physical properties of both topsoil and subsoil must be taken into account. Research is therefore needed on the extent of preferential flow and on methods to measure this in an easy way.

Even though placement of lime on the subsoil significantly reduced PP leaching in the clay soil lysimeters presented in this thesis, further studies including topsoil need to be performed before the full potential of this mitigation strategy can be determined. In addition, a cost-effective, field-scale technique for even distribution of lime on top of the subsoil has to be developed. However, based on the results presented in this thesis and many other studies, P leaching in most clay soils can probably be reduced considerably by liming, either on top of the subsoil or in any other way.

9 Svensk sammanfattning

Övergödning är ett stort miljöproblem i många sjöar, vattendrag och i Östersjön. Jordbruket är den enskilt största källan när det gäller fosfortillförsel till Östersjön, och står för ca 40 % av Sveriges totala antropogena fosforbelastning. År 2000 antogs EU:s ramdirektiv för vatten, vilket syftar till att alla sjöar, vattendrag, kustvatten och grundvatten ska ha god ekologisk status. Dessutom antog Östersjöländerna 2007, inom ramen för HELCOM, en gemensam åtgärdsplan, Baltic Sea Action Plan (BSAP), vars syfte är att ytterligare driva på arbetet med att minska näringsbelastningen på Östersjön. Detta innebär att behovet av att minska fosforförlusterna från jordbruksmark är stort.

Under lång tid ansågs fosfor främst försvinna från jordbruksmark via erosion och ytavrinning, och den mesta forskningen relaterad till fosfor har därför skett på matjorden och dess egenskaper. På senare tid har dock utlakning av fosfor uppmärksammats, och anses idag vara den viktigaste förlustvägen på många fält. I många jordar har fosforläckaget varit svårt att förutsäga baserat enbart på matjordens egenskaper, och den tidigare ofta negligerade alven har därmed allt mer frekvent lyfts fram som en viktig parameter. För att minska fosforförlusterna från jordbruksmark är kännedom om både matjordens och alvens kemiska och fysikaliska egenskaper av stor vikt. Kunskap om i vilken omfattning fosfor binds och frigörs i alven är i nuläget begränsad, då väldigt lite forskning har gjorts inom detta område.

Studierna som beskrivs i denna avhandling undersökte påverkan av olika kemiska markegenskaper i matjord och alv på fosforläckaget, samt om alven i två sandjordar (Mellby och Nåntuna) och två lerjordar (Lanna och Bornsjön) fungerade som en källa eller sänka för fosforläckage. Ostörda jordprofiler (lysimetrar) med (1.05 m djupa) och utan (0.77 m djupa) matjord togs ut och installerades i en lysimeteranläggning vid SLU i Uppsala, där fosforläckage mättes kontinuerligt under tre år. Kalk tillfördes till alvens översta del på de jordar där alven inte förväntades fungera som en sänka för fosfor.

Resultaten visade att alven kan fungera både som en källa och sänka för fosfor. Fosforläckaget var mycket högre från sandjorden med måttligt fosforinnehåll i matjorden (Nåntuna) än från sandjorden med mycket högt fosforinnehåll i matjorden (Mellby). Anledningen till detta var ett väldigt högt fosforinnehåll, i kombination med låg sorptionskapacitet, i alven på Nåntuna, samt en väldigt hög sorptionskapacitet i Mellbys alv. Läckaget av löst fosfor från alven i Nåntunajorden var så mycket som 99 % jämfört med det från både matjord och alv, vilket klart visar att den alven fungerar som en källa för fosforläckage. Mellby alv fungerade, tack vare sin höga sorptionskapacitet, som en sänka för fosfor.

Ökad fosformättnadsgrad och ökat fosforinnehåll i alven, samt minskad sorptionskapacitet i både matjord och alv, visade sig vara väl korrelerat med ökat fosforläckage, vilket indikerar att dessa egenskaper skulle kunna användas för att uppskatta fosforläckage. På jordar med makroporflöde i alven kan dock vattentransport genom jorden ske väldigt snabbt, vilket innebär att fosforn inte hinner reagera med sorptionsytorna i alven. På dessa jordar kommer fosforläckaget därför sannolikt att vara direkt kopplat till frigörelsen i matjorden. För att kunna implementera bra och kostnadseffektiva motåtgärder måste fokus således alltid vara på både kemiska och fysikaliska egenskaper i både matjord och alv.

Att placera kalk på alven minskade förlusterna av partikulärt fosfor från båda lerjordarna. Detta skulle således kunna vara en effektiv motåtgärd för att minska fosforläckaget från lerjordar, utan att riskera att påverka växttillgängligheten av fosfor i matjorden.

Kalkning på alven minskade däremot inte fosforläckaget från Nåntuna sandjord, vilket i och för sig var ett förväntat resultat på grund av den låga lerhalten. Nåntunajorden hade väldigt högt fosforinnehåll och låg sorptionskapacitet i alven, och därmed även väldigt höga fosforförluster. Denna jord ligger dessutom precis intill Fyrisån, som några kilometer nedströms mynnar ut i Ekoln – en vik av Mälaren som många somrar är drabbad av kraftiga algblomningar. Att identifiera dessa ’hot spots’ för fosforförluster i landskapet är av stor vikt för att kunna minska näringsbelastningen på sjöar, vattendrag och Östersjön. Motåtgärder mot fosforförluster bör på dessa jordar placeras efter fältet för att så effektivt som möjligt minska fosforförlusterna.

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